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LOG HOUSE PERFORMANCE IN THE 2016 KAIKOURA EARTHQUAKE

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ABSTRACT

This paper describes the performance of log houses in the 2016 Kaikoura earthquake. Most of these houses are in the Mt Lyford village 45 km south-east of Kaikoura.

Typical log houses at Mt Lyford were built using 200mm diameter machined logs. A smaller number of log houses were built with much larger hand-hewn logs of less regular shapes, in traditional log house construction. Most houses were constructed on a concrete slab incorporating the foundations. A small number, especially those on steep sites, had timber poles supporting a timber ground floor platform.

Most of the log houses suffered some lateral movement and subsequent damage. Very few of the houses were damaged beyond repair, and the overall performance was excellent considering the nature of the quake.

One house close to Waiau suffered extreme near-fault shaking, leading to extensive damage, but this is considered to be the result of exceptional ground movement rather than any deficiencies in the design or construction.

INTRODUCTION

Earthquake

The Kaikoura earthquake occurred on 14th November 2016. The epicentre was near Waiau, 60 km south of Kaikoura and 25 km east of Hanmer Springs. The earthquake was characterised by very complex faulting in the area between Waiau and Kaikoura, resulting in "near fault" shaking in a number of localities. The recorded acceleration response spectra at a nearby site and the code design spectra are shown in Figure 1.

Mt Lyford Village

This paper describes the performance of log houses. Most of these houses are in the vicinity of the Mt Lyford village which is a small community of alpine chalets near the Mt Lyford ski area on the Inland Kaikoura Road, 20 km north of Waiau and 45 km south-east of Kaikoura. The village was begun about 20 years ago, and has grown slowly over that time. There is a covenant on the property titles in the village, requiring all buildings to be log houses, or of similar appearance.

Typical log houses in the Mt Lyford Village are shown in Figures 3 to 6. Most of the houses have been built using machined logs as shown in Figure 2 with a 200mm diameter, produced locally. Most of these houses are constructed on a concrete slab incorporating the foundations. A small number, especially those on steep sites, are of "pole house" construction with timber poles embedded in concrete foundation, supporting a timber ground floor platform.

Typical houses with small logs are shown in Figures 3 to 5. Typical slab on grade foundations are shown in Figures 3 and 6. Houses on pole supports with diagonal sub-floor bracing are shown in Figures 7 and 8.

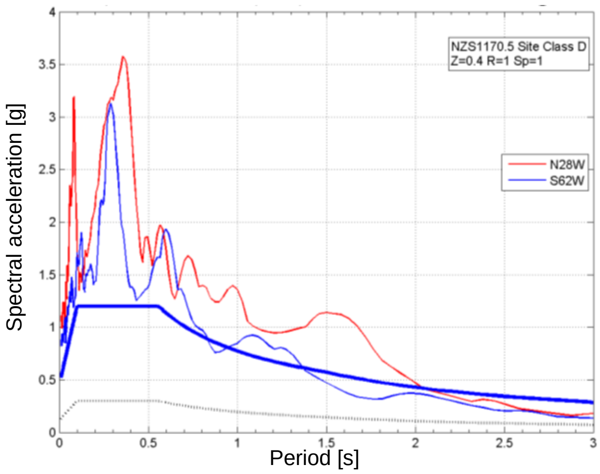

Figure 1: 5% damped elastic acceleration response spectra at the Te Mara Farm Waiau station (WTMC). Solid line ULS, dotted line 0.25 ULS [1].

A small number of log houses in the Mt Lyford area are built with much larger hand-hewn logs of less regular shapes, in the style of more traditional log houses, as shown in Figures 9, 10 and 38.

Scope

This paper focusses on structural and non-structural earthquake damage to the above-ground parts of log houses. All inspected houses were built with machined or hand hewn round logs, so no information can be provided on the behaviour of 'blockhaus' style houses such as Lockwood or Fraemohs. Foundations and geotechnical issues are only referred to where appropriate. Many of the houses had

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geotechnical damage to the surrounding ground, which affected amenity and access, but not the main structure. A few houses lost support due to slope stability issues.

Figure 2: Typical machined logs.

Figure 3: Two storey log house with slab on grade foundation.

Figure 4: Two storey log house on slope with pole foundation.

Figure 5: Two storey log house.

Figure 6: Two storey log house with slab on grade foundation.

Figure 7: Two storey log house with pole foundation.

Figure 8: Pole supports with diagonal sub-floor bracing.

Figure 9: Two storey traditional log house.

Figure 10: Two storey traditional log house with geotechnical damage.

Figure 11: Two storey log house on slope with pole foundation with slope stability failure.

DESIGN METHODS FOR LOG HOUSES

Structural design methods for most log houses are described briefly, as an introduction to the observations of earthquake damage. All walls are constructed with horizontal logs stacked on top of each other, with half-depth notches at the house corners to allow the logs to pass though the corner junction. This requires the bottom logs to be whole logs in one direction and half logs in the perpendicular direction as shown in Figure 12.

Figure 12: Typical connection details with vertical steel rods and anchorage into foundation and half log (sill log).

Gravity Design

Design of log houses for vertical gravity loads is very straightforward. All loads from the roof or from upper floors are supported on internal and external log walls, where the horizontal logs are stacked on top of each other. Most logs have intersecting joints where they cross over each other at the corners of intersecting walls. Intersecting walls are essential to guarantee the out-of-plane stability of the walls. All vertical stresses are perpendicular to the grain, but the stress values are very low because of the large cross section of the supporting structure.

A negative feature of the perpendicular to the grain stresses is that the height of the walls can drop significantly as the logs shrink when they dry out. Construction to reduce or control shrinkage is an important part of log house design and detailing.

Lateral Load Design

As in most domestic construction, lateral loads in log houses are resisted by internal and external bracing walls (all made of horizontal logs). In general, the more walls, the better the resistance to lateral loads, as expected.

Log walls generally resist internal shear forces by friction between logs, with an additional contribution from the notches at the intersecting corners. A further contribution is sometimes provided by the dowel action of vertical steel rods or tie-down anchors. It is essential that the sill log (bottom log), is properly anchored to the foundation, to ensure that sliding of the entire house does not occur.

Overturning moments are resisted by the self-weight of the walls and by vertical steel rods used as tie-down anchors at the ends of the walls. If the hold-down action goes missing and logs uplift, the friction between the logs will be reduced. It is therefore important that the tie rods are re-tightened regularly during the drying out phase of the logs.

Lateral loads below timber ground floors are usually resisted by the cantilever action of short braced piles or by diagonal timber bracing between longer timber poles. No serious damage was observed in the sub-floor bracing of any houses (Figure 8).

There is nothing in the New Zealand Building Code or related documents about design of log houses. North American publications on seismic design of log houses include those by Hahney [2], Popovski [3], Leichti [4], Graham [5, 6], Kessler [7] and Chambers [8].

Typical Details

For houses on concrete slab floors, the most typical hold-down detail is for the sill log (bottom log) to be anchored to the concrete slab with bolts or threaded rods. There are several different details for anchorage to the slab including epoxy, or washer and nuts in a pocket in the concrete or to a cast-in steel angle. It is typical for all the upper logs to be anchored to the bottom log with vertical threaded rods which pass through holes drilled in every log as shown in Figure 13.

Figure 13: Typical connection with threaded rods through the logs.

For houses on raised timber floors, the most typical detail is for the vertical rods to run full height from the top of the top log to the underside of the foundations. The bottom end of the rods is often anchored between double timber bearers as shown in Figure 14.

Figure 14: Typical anchorage with a timber block between floor bearers.

SITE OBSERVATIONS OF DAMAGE

Geotechnical Damage

Many of the houses had geotechnical damage to the surrounding ground. A few houses lost support due to slope stability issues, as shown by the loss of support to the deck in Figure 11.

Horizontal Movement in Log Walls

In a few houses with poor anchorage, the whole house slid horizontally on the foundations, by up to 100mm. Figure 15 shows local sliding of the house in Figure 3. Sometimes the sliding was at the top of the bottom half-log as shown in Figure 16. In a few exceptional cases, objects were trapped under the bottom log, showing that there had been considerable upward movement of the whole wall for a few moments during the earthquake as shown in Figure 17.

Figure 15: Horizontal sliding of the house.

Most houses suffered damage through horizontal sliding between logs, to varying degrees. Sometimes this sliding was concentrated at one or two locations, as shown in Figures 18 and 19. More often the sliding was distributed between many logs as shown in Figures 20 and 21. In either case the sliding resulted in non-structural damage and some permanent distortion. Sliding was sometimes visible at the intersecting corner connections, especially for hand-hewn connections in large irregular logs as shown in Figure 22.

Figure 16: Sliding at the top of the bottom half-log.

Figure 17: Ice-cream lid trapped under bottom log.

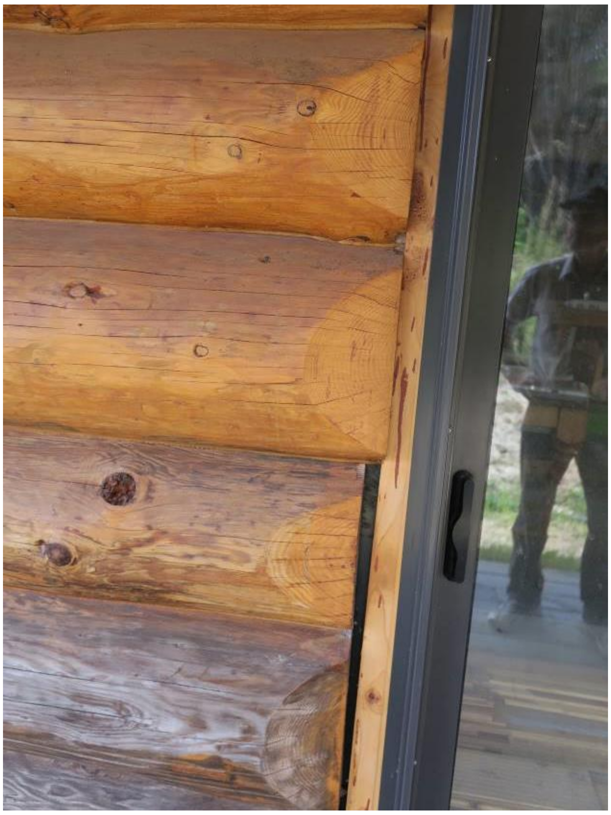

Figure 18: Localized sliding of logs.

Figure 19: Localized sliding of logs.

Figure 20: Sliding of logs resulting in residual drifts of the house.

Figure 21: Sliding of logs resulting in residual drifts of the house.

Figure 22: Sliding of the logs at corners.

Figure 23 shows 60mm horizontal sliding where the bottom end of the tie-down rod was sitting on the top surface of timber decking.

Figure 24 shows horizontal sliding above the lower suspended floor of the house in Figure 4. The large horizontal deformations in this house caused other structural damage including fracture of the post shown in Figure 25.

In general, the machined notches in the houses with 200mm logs tended to provide greater resistance to sliding than the hand-hewn notches in the larger logs. More sliding between large logs may also have been due to the greater mass of these buildings.

Figure 23: Sliding of the logs measured at the vertical rod.

Figure 24: Sliding of the logs on suspended floor.

Figure 25: Fracture of veranda post due to excessive lateral movement.

Tie-Downs for Overturning

Nearly every inspected house showed some damage to vertical tie-down rods. This was most often visible at the bottom end connection. Many examples are shown in the photographs.

Figures 6 and 26 show damage to the unreinforced concrete foundation at a tie-down connection. Some rods were fractured by the tensile load as in Figure 27. Figures 28, 29 and 30 show visible damage at the bottom washers, where the damage is either a result of bending of the washer and some tensile yielding of the steel rods, usually accompanied by wood crushing or wood fracture. In some cases there was crushing of the bottom log as shown in Figure 31.

In houses with timber floors, there were some fractures of the short timber anchoring block between double joists as shown in Figure 32. Reinforcement provided by one owner after the earthquake is shown in Figure 33.

Figure 26: Damage to pocket in concrete foundation due to missing reinforcement.

Figure 27: Fractured tie rod.

Figure 28: Bent washer in concrete pocket.

Figure 29: Bent washer and wood crushing in anchorage block.

Figure 30: Bent washer and wood crushing in bottom log.

Figure 31: Crushing of bottom log.

Figure 32: Failure of timber anchorage block.

Figure 33: Reinforcement of timber anchorage with a steel profile.

Foundation Design

Most foundations performed very well, provided that the land remained stable. There were a few exceptions such as cracking off of the corner concrete shown in Figure 34.

Figure 34: Cracking and spalling of concrete due to large compression forces.

Horizontal Movement in Upper Storeys

Most of the two-storey houses have log walls at the bottom floor and light timber framing with plasterboard lined walls at the second floor. In these cases there was usually much less lateral movement in the upper storey, and therefore little damage to the second storey walls and the roof.

Non-Structural Damage

Almost all houses showed some non-structural damage to internal linings due to differential horizontal movements. Light timber framed walls at the same level as log walls could not accommodate the large lateral deformation of the log walls, resulting in cracked plasterboard lining especially around openings and at wall corners. Permanent lateral deformations resulted in obvious distortions and some doors which could not be closed. Typical cracking of gypsum plasterboard is shown in Figures 35 and 36.

Some hot water cylinders with insufficient restraint fell over, causing additional damage to linings and plumbing, as shown in Figure 37.

In a smaller number of houses there were broken windows or roof damage due to falling chimneys of unreinforced masonry. A few houses had broken windows and there were a small number with damage from falling chimneys.

Figure 35: Typical cracking of gypsum plasterboard.

Figure 36: Typical cracking of gypsum plasterboard.

Figure 37: Damage from insufficiently restrained water cylinder.

Near-Fault House

The authors were directed to one particular log house about half way between Mt Lyford and Waiau, which suffered extreme near-fault shaking, leading to extensive damage. This house is described separately to the others because of the higher level of damage. It is a new house, of large traditional log house construction on a concrete slab, shown in Figures 38 and 39. An indication of the extreme level of local shaking is provided by the rock on the lawn shown in Figure 40, which jumped to a new position over one metre away. The damage to this house is considered to be the result of exceptional ground movement rather than any major deficiencies in the design or construction. Local acceleration amplification due to the local topography, also known as the 'hill crest effect' [9], could have caused the increased shaking of the house.

Figure 38: Two storey traditional log house.

Figure 39: Two storey traditional log house with visible residual drift.

Figure 40: The rock close to the house was moved by about a meter by the earthquake.

Figure 41: Permanent deformation in corner area.

Figure 42: Permanent deformation in corner area.

Figure 43: Large deformation around very stiff circular door frame.

Permanent deformations from horizontal sliding between logs was much larger in this house than in houses at Mt Lyford, as shown in Figures 41 and 42. There was unusual movement around the circular steel frame of the front door shown in Figure 43 where there was upwards movement of logs due to the shape of the door frame. The picture trapped under the bottom log in Figure 44 shows that there was significant vertical movement of some log walls.

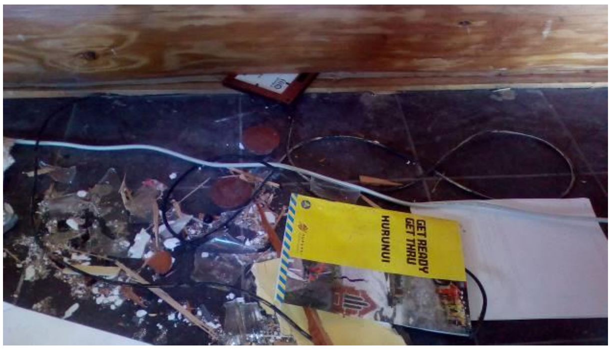

Figure 44: Trapped picture frame under sill log.

Figure 45 shows yielding of tensile tie rods. Significant damage occurred at the bottom log connection to the concrete slab, especially where there was a bottom half-log. A typical undamaged whole log is shown in Figure 46, whereas Figures 47, 48 and 49 show severe splitting of bottom half-logs in the transverse direction. This splitting was accentuated by the presence of tie rods (to resist uplift), dowels (to resist shear) and pre-cutting of logs at door and window opening to control shrinkage.

Figure 45: Yielding failure or fracture of tension rod.

Walls with no cross logs were more badly affected, as shown in Figures 50, 51 and 52 where some logs have split in half exposing the tie-down rods and shear dowels.

These large movements caused massive non-structural damage, as expected. Some typical downstairs damage is shown in Figures 53 and 54, and in Figure 55 which shows the kitchen and the hot water cylinder. Damage in the upper storey was much less, as shown in Figure 56.

Figure 46: Initiation of splitting in logs, undamaged bottom log.

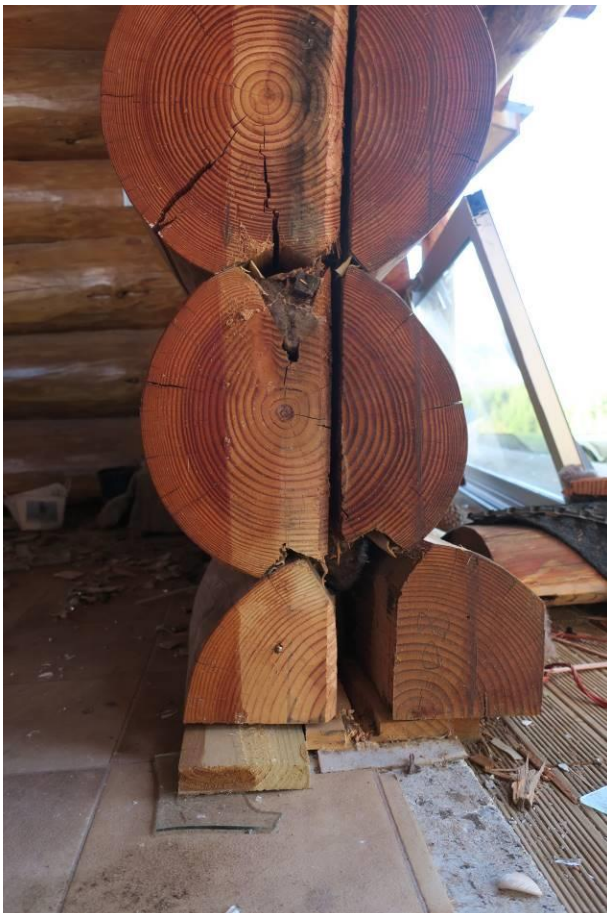

Figure 47: Splitting of bottom log.

Figure 48: Splitting of logs weakened by tie rods and shear dowels.

Figure 49: Splitting of bottom log weakened by vertical slot at door frame.

Figure 50: Wall stability failure and splitting of logs.

Figure 51: Splitting of log.

Figure 52: Splitting of log due to weakening by dowels, tie rod and vertical slot at door frame.

Figure 53: Typical damage to doors and windows due to large horizontal deformation.

Figure 54: Typical damage to light timber framing walls lined with plasterboard.

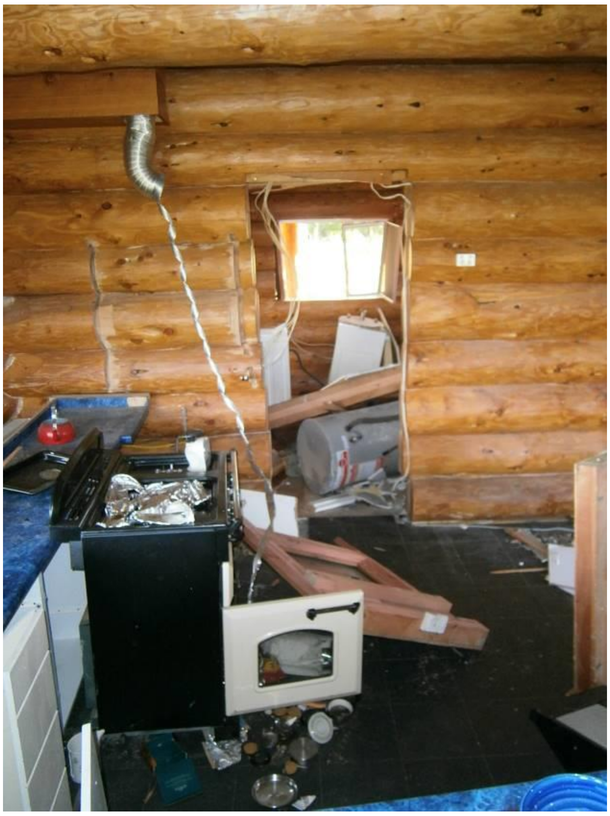

Figure 55: Typical damage from falling or sliding of heavy objects.

Figure 56: Damage in the upper storey was very limited.

REPAIR STRATEGIES

For the majority of houses which suffered minor damage, simple repair strategies are available. If the small permanent horizontal movement is acceptable, repair can consist of tightening tie-downs and repairing non-structural damage. Houses with larger horizontal movement may be able to be pulled back into line with turfers or jacks after releasing any highly stressed tie-down rods. Fractured rods can generally be replaced, depending on access. There are a large number of anchorages with minor damage, most of which can be repaired easily.

Repairs to damaged linings and other non-structural damage will be required in almost every building.

For a very small number of houses, demolition and rebuilding will be required. This applies to one or two houses which had insufficient internal walls and poor detailing, and the one house which suffered extreme near-fault excitation.

CONCLUSIONS

- Most log houses generally exhibited good or excellent behaviour.
- Houses with machined logs tended to have less horizontal movement than those with heavier traditional logs.
- There was non-structural internal damage to most houses, which will require repair of gypsum plasterboard linings.
- Many houses had no significant structural damage.
- Where structural damage did occur it was often the result of an inadequate number or irregular location of internal walls, accompanied by damage to tie-down rods.
- Tie down anchorages were often poorly designed and detailed.
- There was excessive damage to one particular house, subjected to near-fault shaking.

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